

# **SUPPRESSION OF A NON-PREMIXED FLAME BEHIND A STEP**

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## ABSTRACT

Because of its many positive attributes, halon 1301, or trifluorobromomethane ( $\text{CF}_3\text{Br}$ ), has been used as a fire extinguishing agent in many applications including aircraft, ships, and specialized structures. Due to its high ozone depletion potential, however, world-wide production was halted in 1994. In the search for a long-range replacement, novel types of extinguishing agents and delivery mechanisms are under development. To gauge the suitability of a replacement agent, methods are needed to evaluate the material's suppression effectiveness under conditions that relate to field applications. In this study, a laboratory-scale facility has been developed to screen the suppression effectiveness of gaseous agents, powders, and solid propellant gas generator concepts that are being considered as replacements for halon 1301. The facility features a pool fire stabilized behind an obstruction, which is known to be a highly challenging suppression configuration. The character of the flame and the impact of the air flow, propane flow, obstruction geometry, and rate of agent addition on the amount of material needed for suppression are examined for  $\text{N}_2$  and  $\text{C}_2\text{HF}_5$  and compared to  $\text{CF}_3\text{Br}$ . The impact of the injection process on the flow field and the transport of the agent downstream are examined. Direct numerical simulation of the suppression event is shown to successfully predict the quantity and rate of  $\text{N}_2$  required to extinguish the flame based upon a published global reaction rate for premixed propane/air flame propagation.

## INTRODUCTION

Agent suppression effectiveness is typically measured by experiments in quasi-laminar diffusion flames established in the cup burner or counter-flow burner [1]. Those experiments are conducted by increasing the agent flow slowly until a critical mole fraction is achieved in the oxidizer and flame extinction is observed. In practice, however, agents designed to replace  $\text{CF}_3\text{Br}$  are discharged rapidly, not quasi-statically. Solid propellant gas generators (SPGGs), for example, typically discharge in 60 ms to 600 ms. A robust and repeatable means to evaluate the effectiveness of different formulations and burning rates is required, something that is impossible with conventional screening devices.

A few researchers have investigated the effectiveness of an agent in suppressing baffle stabilized flames [3-7]. Hirst, Dyer, and coworkers developed a wind tunnel to explore the impact of step height, air flow, pressure, and agent mass requirements on the suppression of a pool fire [3,4,5]. Hirst et al. [4] concluded that liquid pool fires established behind an obstacle are highly challenging to extinguish. This is recognized in the gas turbine industry where combustors and afterburners exploit the enhanced stability associated with combustion in a recirculation zone [2]. Hamins et al. [6] developed a phenomenological model to characterize the stability of baffle stabilized fires. Takahashi et al. [7] examined the character of methane/air flames for varying air velocity and baffle step height. The amount of halon 1301 required to suppress the flames as a function of the flow parameters and injection interval was also measured.

This paper describes an experimental facility and numerical modeling study of the suppression effectiveness of different agents discharged in a transient manner into a baffle stabilized pool fire. The *transient application recirculating pool fire* (or TARPF) is designed to simulate challenging fire situations and to precisely control the air flow amount of agent, discharge rate, and discharge duration.

Air is metered through a sonic orifice to overcome the unintended disruption that occurred in previous studies during the agent discharge period [3-5,7]. The influence of common geometric complexities (baffles, a backward-facing step and a cavity) on flow field dynamics and flame stability is investigated, and a relationship is constructed between the mass of agent necessary for suppression and the agent

injection duration. Direct numerical simulation of flame suppression is used to help explain the observations.

## EXPERIMENTAL FACILITY

The TARP facility, shown schematically in Fig. 1, consists of a 2.5 m long steel duct with a square cross section 92 mm on a side. A compressor supplies dried ambient air, which is monitored using a calibrated sonic orifice and a piezoelectric pressure transducer. A diffuser (with a 12° half-angle expansion) provides a smooth transition from the 38 mm air line to the square duct. A honeycomb flow straightener and mixing screens are located downstream of the diffuser. A 26 mm high, 0.3 m long stainless steel ramp is located just before the burner for most experiments. Baffles between 10 mm and 55 mm high and 6 mm thick are used in lieu of the ramp in a number of experiments. The burner is located on the floor of the duct, directly downstream of the ramp or baffle, and consists of a sintered bronze plate, 92 mm wide by 190 mm long. Commercial grade propane, metered by an electronic mass flow controller, is the fuel. The sintered metal plate is cooled by water flowing through copper tubes. The flame is viewed from above and the side through glass windows. The expanded relative uncertainty in the flows of fuel and air are  $\pm 5\%$  of the measured value based upon the manufacturers' specifications for the metering orifice and mass flow controller. (Note that this and all other quantified uncertainties are for a coverage factor of 2, unless explicitly stated otherwise.)

The flame is ignited by a spark across two protruding electrodes located on the side wall of the test section 20 mm above the surface of the burner and 20 mm downstream of the step. For some experiments, a heated plate is inserted into the flow from the bottom surface of the duct directly downstream of the burner to create a cavity and can act as a possible source for reignition.

Nitrogen (0.99995 mole fraction pure),  $\text{CF}_3\text{Br}$  (commercial grade), and  $\text{C}_2\text{HF}_5$  (commercial grade) are stored as gases in one and two liter stainless steel vessels with the pressure monitored by a high speed (1 ms response) piezoelectric transducer, and the temperature is measured with a chromel-

alumel (76  $\mu\text{m}$  diameter) thermocouple. An electronic timer controls the interval (10 ms to 1000 ms) that the a solenoid valve on the agent vessel remains open. The agent passes through a 6 mm diameter orifice before it is injected through two opposed radial ports into the air passage upstream of the diffuser. Because the air is choked at the metering orifice plate, the introduction of the agent is accomplished without altering the total air flow. The velocity in the tunnel upstream of the burner is measured with a 3 mm diameter pitot tube. The relative concentration of  $\text{C}_2\text{HF}_5$  in the air stream during a discharge with no flame present is measured with an instrument developed by Mulholland et al. [8] based upon infrared absorption.

A 30 Hz video camera records the flame and is an indicator of suppression success. For some experiments, a high speed digital camera (1000 Hz) is used to investigate the suppression dynamics. A computer monitors the flow controllers, pressure transducers, and thermocouples, and sends a signal to the electronic timer to open and close the solenoid valve while releasing the flow of suppressant. Pressure and temperature in the agent storage vessel and the output from the pitot tube are measured at a frequency of 1000 Hz during the discharge process.

The mass of the gaseous agent released is determined from the change in pressure and temperature in the storage vessels [6]. The expanded uncertainty (with a coverage factor of 2) in the calculated mass is  $\pm 2 \%$ , with a minimum absolute uncertainty of  $\pm 0.12 \text{ g}$  attributable to the resolution of the pressure transducer. The piezoelectric pressure transducers can follow the transient but the thermocouple is too slow, so the transient temperature in the agent storage vessel is estimated by assuming an isentropic expansion of an ideal gas. From the temperature and pressure measurement, the rate of suppressant addition to the incoming air,  $dm/dt$ , is estimated using an equation of state [6]. The expanded uncertainty of  $dm/dt$  is  $\pm 2 \text{ g/s}$ , with a coverage factor of 2.

## EXPERIMENTAL RESULTS

### Facility Characterization

The facility was operated over a range of propane and air flows to examine the flame behavior. Blow out can be achieved either by increasing the air flow or decreasing the propane flow. At low air velocities, a fluctuating laminar flame is anchored on the top downstream edge of the step or baffle and extends well downstream of the porous plate. The flame produces soot, which quickly coats the side-wall window. As the velocity increases, the flame becomes turbulent and less luminous, and the soot deposition ceases. Near blow-out, the orange color disappears and the visible blue flame shrinks to a small eddy at the base of the obstacle. With the backward-facing step installed, an average air velocity (found by dividing the volumetric flow, corrected to 101 kPa and 20 °C, by the duct area above the step, 92 mm by 66 mm) of over 23 m/s is necessary to blow out the flame if the propane flow is greater than 33 mL/s (corresponding to a velocity of 1.9 mm/s).

Two air flows were chosen to evaluate the ability of the agents to suppress the propane pool fire stabilized by the backward-facing step. The low and high mean air velocities (just above the step) were  $2.1 \text{ m/s} \pm 0.2 \text{ m/s}$  and  $5.4 \text{ m/s} \pm 0.2 \text{ m/s}$ , respectively. Corresponding propane flows of  $33 \text{ mL/s} \pm 2 \text{ mL/s}$  and  $85 \text{ mL/s} \pm 2 \text{ mL/s}$ , respectively, were utilized. The low flow condition corresponds to what Takahashi et al. [7] describe as regime I suppression (rim-stabilized flame), and the high flow is transitional between regimes I and II (intermittent turbulent flame).

The velocity distribution of the air 76 mm upstream of the burner was measured with the pitot tube at five locations across the duct for both the high and low flow conditions. With no flame present, the velocity profile was found to be flat within 5 % over the central three-fourths of the duct. The boundary layer above the step was measured to be less than 7 mm thick.

The facility is designed to impulsively introduce suppressant without altering the air flow. This is achieved by maintaining a choked condition for the air independent of modest changes in downstream pressure generated by the injection process. The pitot tube was used to measure the instantaneous flow

76 mm ahead of and 5 mm above the backward step during the discharge of  $C_2HF_5$  into the air stream for the two different air flow conditions (without fuel flowing). The dashed lines in Fig. 2 show the combined effect of the velocity ( $V$ ) and density ( $\rho$ ) change,  $V(\rho/\rho_O)^{1/2}$ , created by the injection process, where  $\rho_O$  is the initial density of the air stream. Figure 2a is for the low air flow condition and a high rate of agent discharge; Fig. 2b represents a high air flow with a low rate of agent addition. The pressure,  $P$ , in the agent storage vessel is also plotted in Fig. 2, from which the rate of  $C_2HF_5$  mass added,  $dm/dt$ , is calculated. The injection interval is  $130 \text{ ms} \pm 5 \text{ ms}$  for both cases, but the amount of agent added in Fig. 2b is only 1/3 the amount added in Fig. 2a because the single 1 L agent storage vessel was used in the former case, while the 1 L and 2 L agent storage vessels were used in tandem for the latter.

The sizable increase in  $V(\rho/\rho_O)^{1/2}$  seen in Fig. 2a within 0.10 s of the passage of the acoustic wave results from the slug of air between the injector and the pitot tube being shifted downstream by the addition of a large amount of agent. High speed video images of the flame during the discharge corroborate this description. The shift is barely discernable in Fig. 2b since the amount of agent added is small relative to the flow of air. The time that the agent itself arrives at the pitot tube is limited by the bulk convection and the distance the probe is downstream of the point of injection (1.1 m). The times of arrival of the agent at the pitot tube can be estimated to be 0.71 s and 0.29 s for the conditions in Figs. 2a and 2b, respectively. Interpretation of the pitot signal is complicated by the much higher density of  $C_2HF_5$  as compared to air.

To determine the presence of the agent independent of velocity, the infrared absorptance,  $\alpha$ , of  $C_2HF_5$  across the width of the duct was measured and plotted in Fig. 2. The viewing port is 2.3 m downstream of the injector and 1.1 m downstream of the pitot tube. The absorptance pulse in Fig. 2b is similar in shape to the rate of discharge, but about 0.1 s wider. Nonuniform mixing of the agent with air as it flows over the step and into the recirculation zone contributes to the long absorptance tail that is evident for over a second in Fig. 2a, although the agent injection duration was only 0.13 s.

## N<sub>2</sub> and CF<sub>3</sub>Br Suppression Experiments

The mass of suppressant required to extinguish the step-stabilized fire is a function of both the air flow and the injection interval, whereas the magnitude of the propane flow was found not to have much affect on the required mass of suppressant. As the injection interval increases from about 0.05 s to almost 0.40 s, the minimum mass required increases ~3 times. Almost 10 g of N<sub>2</sub> is required when the injection interval is 0.37 s  $\pm$  0.01 s for the high air flow; 4.8 g  $\pm$  0.2 g of N<sub>2</sub> is needed for the low flow condition.

Experiments were conducted with and without the reignition obstruction shown in Fig. 1 and another experiment was conducted with the backward step replaced by a straight baffle protruding 25 mm perpendicularly from the lower surface. The amount of N<sub>2</sub> necessary for suppression was unchanged for these three configurations within the uncertainty of the measurements. Experiments were also conducted with a 10 mm baffle and a 55 mm baffle. The short baffle produces a fire that is measurably easier to extinguish, and the 55 mm baffle yields fires that are more difficult to extinguish. For example, with the air velocity at 3.9 m/s (based upon the full duct cross-section) and the nitrogen injection interval around 0.10 s, the 10 mm, 25 mm and 55 mm obstructions required 3.4 g, 3.9 g and 4.3 g of N<sub>2</sub> to extinguish the fire, respectively, within an uncertainty of  $\pm$  0.2 g.

Figure 3 is a plot of the minimum agent mass fraction that extinguished the fires ( $\beta$ ) as a function of the agent injection time interval ( $\Delta t$ ) for both N<sub>2</sub> and CF<sub>3</sub>Br. The parameter  $\beta$  is defined as the average mass flow of agent during the injection interval divided by the sum of the agent and bulk air flows. The data represent experiments conducted over a range of conditions including air velocities (defined above the obstacles) that varied from 2 m/s to 9 m/s, propane flows from 33 mL/s to 85 mL/s, and baffle heights between 10 mm and 55 mm, in addition to the 25 mm backward step. The open and closed symbols represent the low and high air flow conditions, respectively. Figure 3 shows that  $\beta$  decreases with increasing injection time interval for all obstacle types and both agents. The highest mass fraction requirements were consistently for the low air flow conditions. For some experiments, the value



of  $\beta$  was as large as nearly 0.8 for short injection intervals. The most challenging geometric configuration was the 55 mm baffle, followed by the 25 mm obstacles, and the 10 mm baffles. There was little difference in  $\beta$  between the 25 mm step, 25 mm cavity and the 25 mm baffle and those data are presented as one group in Fig. 3. The effectiveness of  $\text{CF}_3\text{Br}$  was compared to that of  $\text{N}_2$  using the 25 mm high backward step. The 1 L storage vessel was used to accentuate the pressure change associated with the small quantities of  $\text{CF}_3\text{Br}$  required for suppression. Only  $1.6 \text{ g} \pm 0.2 \text{ g}$  of  $\text{CF}_3\text{Br}$  injected for 100 ms was needed to extinguish the flame under the high air flow conditions (corresponding to  $\beta \cong 0.3$ ), as compared to  $3.9 \text{ g} \pm 0.2 \text{ g}$  for  $\text{N}_2$  as agent ( $\beta \cong 0.5$ ).

## ANALYSIS

### Data Correlation

For premixed flames stabilized by a baffle in the middle of the flow field, the rate of agent entrainment from the free stream into the recirculation zone was suggested by Winterfeld [9] to be proportional to the ratio of the baffle size to the free stream velocity. In the current work, the baffle size is taken as the obstacle height,  $h$ . The bulk free stream velocity during the discharge event is determined from the volume flow of air plus agent,  $V'_{\text{air}} + V'_{\text{agent}}$ , divided by the cross-sectional area above the obstacle,  $(L - h)L$ , where  $L$  is the length of the side of the square duct.

A characteristic time,  $\tau$ , for mixing of the agent into the flame zone can be defined in terms of the bulk flow and the obstacle size as:

$$\tau \equiv \gamma h / \{(V'_{\text{air}} + V'_{\text{agent}}) / [(L - h)L]\}, \quad (1)$$

where  $\gamma$  is an empirical non-dimensional parameter that relates the ratio of the distance that a fluid element travels within the recirculation zone to the obstacle height. The recirculation zone behind a backward step (with no combustion) is typically 8 to 10 times the height of the step. Thus, the distance traveled in a single circumnavigation of the recirculation zone should be about twice this amount, or 16 to 20 step sizes. Evaluating Eq. (1) for the range of flows and baffle heights examined in the current

study and using a value of 20 for  $\gamma$ ,  $\tau$  is found to vary between 0.02 s and 0.20 s.

Hamins et al. [6] found that for a specified injection duration it is possible to relate the mass fraction of agent in the free stream required to achieve extinction to  $\tau$ :

$$\beta/\beta^* = [1 - \exp(-\Delta t/\tau)]^{-1}, \quad (2)$$

where  $\beta^*$  can be found experimentally by flowing agent continuously into the air stream at increasing rates until extinction occurs. If the air flow is low enough, the value of  $\beta^*$  is expected to be similar to the cup burner extinction requirements [6]. For propane, Trees et al. [1] found this value to be 0.320 for  $N_2$  and 0.172 for  $CF_3Br$ . For laminar diffusion flames strained at intermediate rates, Trees et al. [1] showed that the minimum extinction mass fraction of agent in a counterflow flame decreases from the cup burner value when the strain rate is  $50 \text{ s}^{-1}$  to much smaller values for a strain rate of  $400 \text{ s}^{-1}$ . Although the flow in the recirculating region behind an obstacle is much more complicated than in a counterflow flame, the strain rate in the current study should scale with  $1/\tau$ . When the flow of air is increased sufficiently, the flame becomes strained to the point that agent is not needed for extinguishment (i.e.,  $\beta^* \rightarrow 0$ ) and the flame blows out.

Takahashi et al. [7] correlated the mole fraction of  $CF_3Br$  required for suppression in a manner similar to that used here for  $\beta$  in suppression of their baffle-stabilized methane flames in a rectangular duct. Agent suppression requirements for baffle heights of 32 mm and 64 mm collapsed to a single curve when plotted against the injection time normalized by the ratio of the step height to the free stream air velocity (7.1 m/s). The velocity increase due to the agent flow was not accounted for, but satisfactory correlation of the results was obtained because the fraction of  $CF_3Br$  injected into the air stream was small. That approximation is not used in this study because nitrogen can constitute more than 2/3 of the total flow during the injection interval.

Takahasi et al. [7] found the value of  $\beta^*$  to be slightly less than the cup burner value. Others have found different results. Dyer et al. [10] found that  $\beta^*$  was greater than the cup burner value in nitrogen suppression measurements of baffle stabilized kerosene pool fires with air speeds below

0.2 m/s. Hamins et al. [6] arrived at a similar conclusion when  $C_2HF_5$  and  $C_3HF_7$  were used to suppress heptane pool fires under low air flow conditions.

The data in Fig. 3 have been normalized by their respective cup burner values and characteristic mixing times, and are replotted as the gray symbols in Fig. 4. When viewed this way, the geometric, flow, and chemical differences among all the experiments conducted in the current study roughly collapse to a single curve. Equation (2) is shown as the dotted line in Fig. 4. Although the simple correlation helps explain the overall trends, a more sophisticated analysis is necessary to account for discrepancies due to the different chemical activity of the two agents, the different agent mixing patterns such as those shown in Fig. 2, and the difference between the cup burner value and  $\beta^*$ .

### Direct Numerical Simulations

To better understand the dynamics of the suppression event, a computational fluid dynamics (CFD) model was used to simulate the baffle and step-stabilized suppression experiments. Some recent studies have numerically modeled flow past an obstacle, but there are no investigations that we are aware of that have used CFD to model suppression by an agent in such a configuration. Liou and Hwang [11] used a two dimensional CFD model to study the residence time of tracer particles within the recirculation zone of a backward-facing step. Weller et al.[12] applied large eddy simulation techniques (LES) in three dimensions to study a premixed turbulent flame stabilized by a backward-facing step. Here, a low Mach number CFD model is applied to study the dynamics of the suppression event in the TARPF facility. The transport algorithm is based on a previously developed large eddy simulation fire model [13]. The sub-grid scale turbulence model is not used here, but rather the coefficients of viscosity, thermal conductivity and mass diffusivity from kinetic theory and empirical extrapolation are implemented [14]. Thus, the calculations are direct numerical simulations.

Both two and three dimensional simulations were performed. The advantage of the two dimensional calculations is that greater spatial and temporal resolution can be exploited. The

disadvantage is that much of the complex structure of the turbulent flame cannot be simulated. Three dimensional calculations are much costlier to perform, but yield a great deal of information about the flame structure. Flame chemistry is approximated as a one-step, finite-rate reaction of propane and oxygen:  $\text{C}_3\text{H}_8 + 5 \text{O}_2 \rightarrow (\text{Products})$ . The reaction rate is given by the global expression based on the premixed flame studies of Westbrook and Dryer [15],

$$d[\text{C}_3\text{H}_8]/dt = -A [\text{C}_3\text{H}_8]^a [\text{O}_2]^b \exp(-E/RT) \quad (3)$$

where  $A = 8.6 \times 10^{11}$ ,  $E/R = 15.1$ ,  $a = 0.1$ , and  $b = 1.65$  (in units of cm, s, mole, and K). The heat of combustion of propane is 46,400 J/g. It is assumed that 20% of the chemical energy is radiated from the flame to the surrounding walls for the diluted near-extinction propane flames. A sensitivity analysis shows that the agent concentration requirements at extinction increase by 15% if the radiation-loss parameter is set equal to zero.

The solution of the conservation equations governing the flow in the tunnel is computed on uniformly-spaced grids spanning a plane 552 mm long and 92 mm high (576 by 96 cells) in two dimensions or a volume 552 mm long, 92 mm wide and 92 mm high (256 by 48 by 60 cells) in three dimensions. The reactant stream consists of oxygen, nitrogen and propane. Nitrogen is used to represent the products of combustion to reduce computational time. As in the experiments, propane is introduced through a 190 mm long by 92 mm wide slot at a uniform rate of 33 mL/s. Air and agent are introduced into the domain 100 mm upstream of the step with a top hat velocity profile. A constant ambient pressure is assumed at the downstream boundary. Ignition is achieved by momentarily heating up a small wall region just downstream of the step. At all other wall locations, the temperature is maintained at 200 °C. Suppression is distinguished from non-suppression in the computations when the reaction in Eq. (3) ceases everywhere.

Figure 5 shows a sequence of images from a 2D simulation that illustrates the dynamics of the suppression event. The first image shows the flame just prior to discharge of the agent, in this case nitrogen, into the air stream. Upon injection, the flame is disturbed by a large vortex generated by the

pressure pulse. Due to the low Mach number approximation, the gas upstream of the step is essentially incompressible, and the velocity jump from 2.1 m/s to 5.7 m/s is conveyed to all points in the flow domain in about 0.02 s (consistent with the pitot probe measurements in Fig. 2 and the high speed video). Thus, even before the agent arrives at the step, the flame has been dramatically transformed as a large vortex is generated. This produces a pathway (see the velocity vectors in Fig. 5) that allows the agent to penetrate the region behind the step, where it mixes with the reactants and suppresses the flame through cooling and dilution. Figure 4 shows that the numerical suppression calculations (plotted as diamonds) are in good agreement with the experimental results.

## SUMMARY AND CONCLUSIONS

A transient application, recirculating pool fire (TARPF) facility has been built for screening the suppression effectiveness of halon 1301 replacements. Nominal air velocities between 2 m/s and 23 m/s flowing over a backward-facing step and baffles that are 10 mm to 55 mm high were examined. Because the air is metered with a sonic orifice, the injection of agent does not modulate the air flow. The minimum amount of agent for flame extinguishment is substantially and directly affected by the air velocity and the interval of injection. The height of the obstacle, whether it is a baffle or a backward facing step, and the propane blowing velocity have only a minor influence on the mass of agent needed for suppression.

A simple mixing model is useful to explain the observed trend of decreasing suppressant mass fraction with increasing injection duration, even for agents as different as  $\text{CF}_3\text{Br}$  and  $\text{N}_2$ . Several areas, however, require further investigation including the effect of the air flow on the steady-state extinction mass fraction of agent, the relationship between agent injection and its concentration history at the flame, and the observed differences in the normalized mass fractions of  $\text{CF}_3\text{Br}$  and  $\text{N}_2$  for very short injection time intervals. The success of the direct numerical simulation of the suppression of the baffle-stabilized flame by  $\text{N}_2$  is encouraging, and will be pursued for chemically active agents.

The ability to measure the relative effectiveness of alternative agents is key to the development of new fire suppression systems. The physical and chemical properties, and the manner of storage and release of the next generation suppression systems may be quite unlike  $\text{CF}_3\text{Br}$ , but their effectiveness must still be bench-marked against it. The TARP facility provides the means to screen gaseous agents, powders, and solid propellant gas generator concepts in the laboratory for applications in protected spaces involving baffle-stabilized pool fires.

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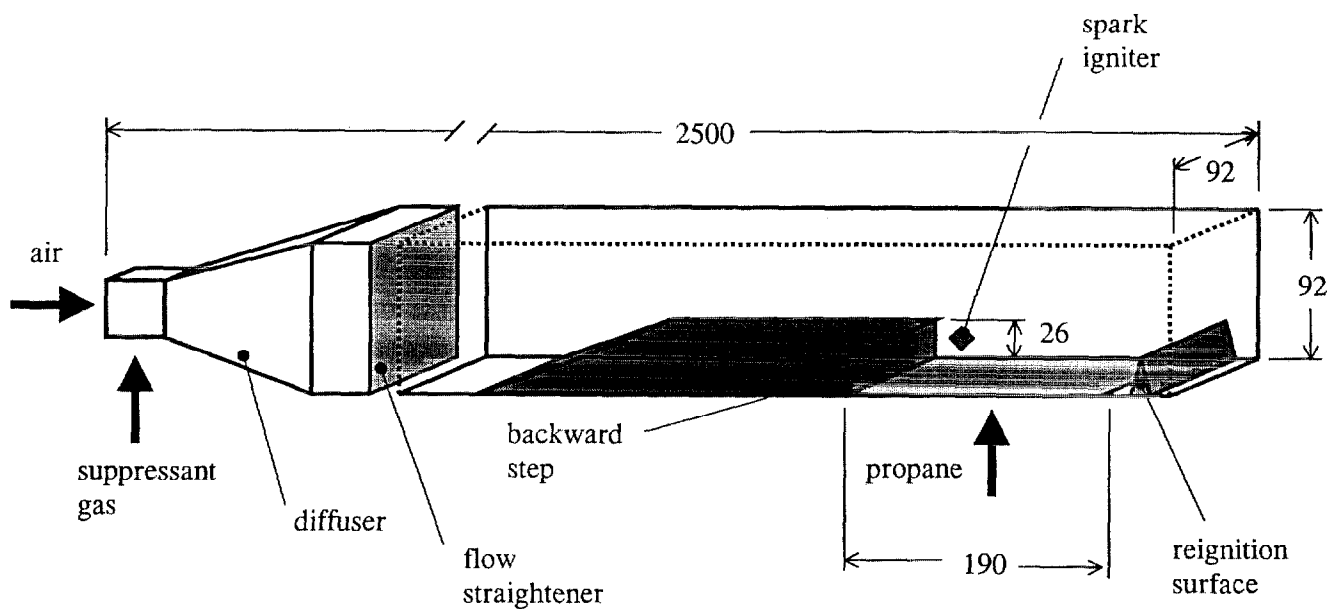


Figure 1. Schematic of step-stabilized pool fire apparatus. Dimensions are in millimeters.



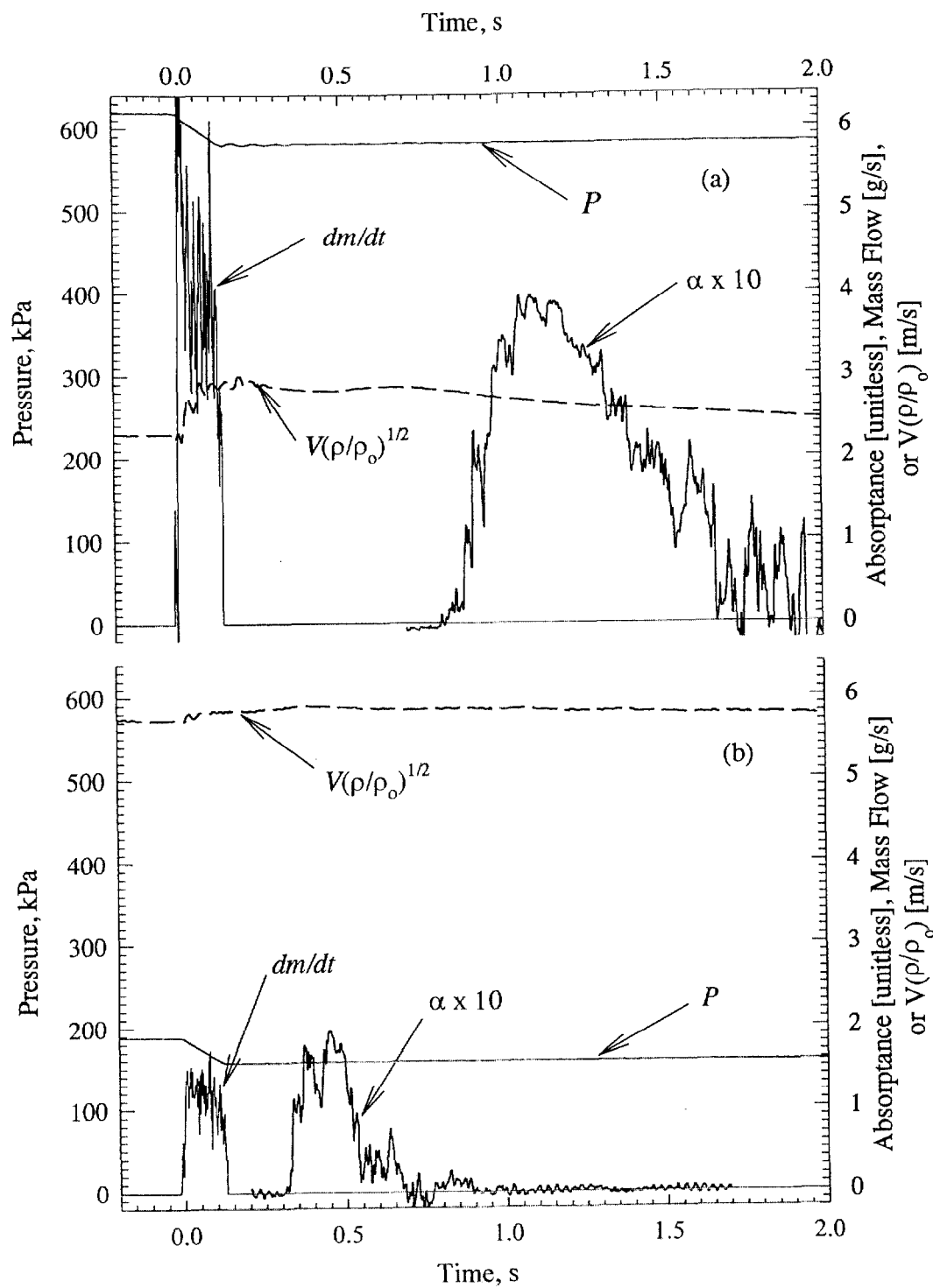


Figure 2. Bottle pressure, agent mass flow, velocity above step, and IR absorbance 1 m downstream of step during 0.125 s discharge of  $C_2HF_5$ ; (a) low air flow, high agent flow, (b) high air flow, low agent flow.

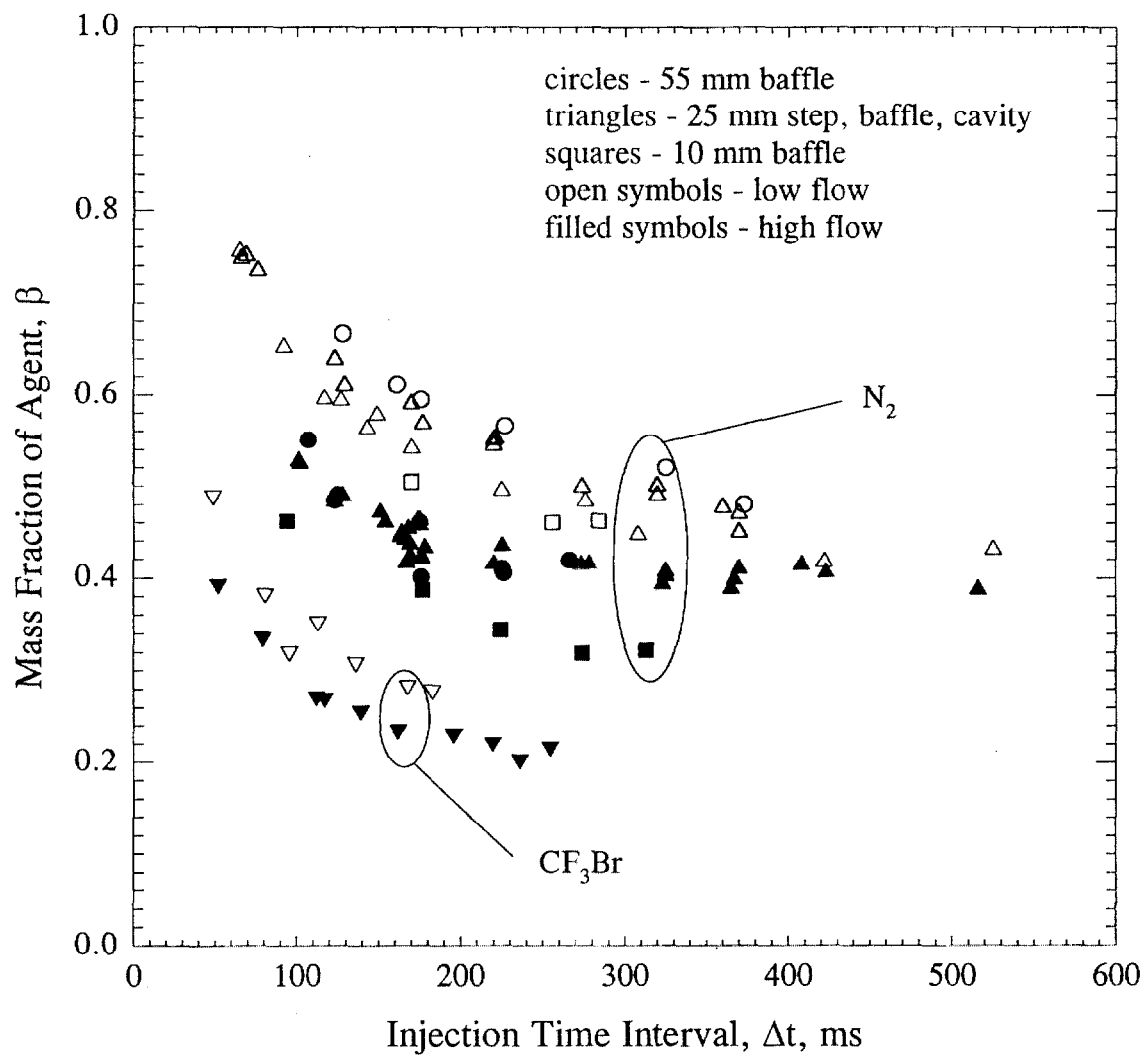


Figure 3. Mass fraction of agents ( $N_2$  and  $CF_3Br$ ) added to air at extinction boundary for high and low flow conditions, as a function of the injection time interval and obstacle geometry.

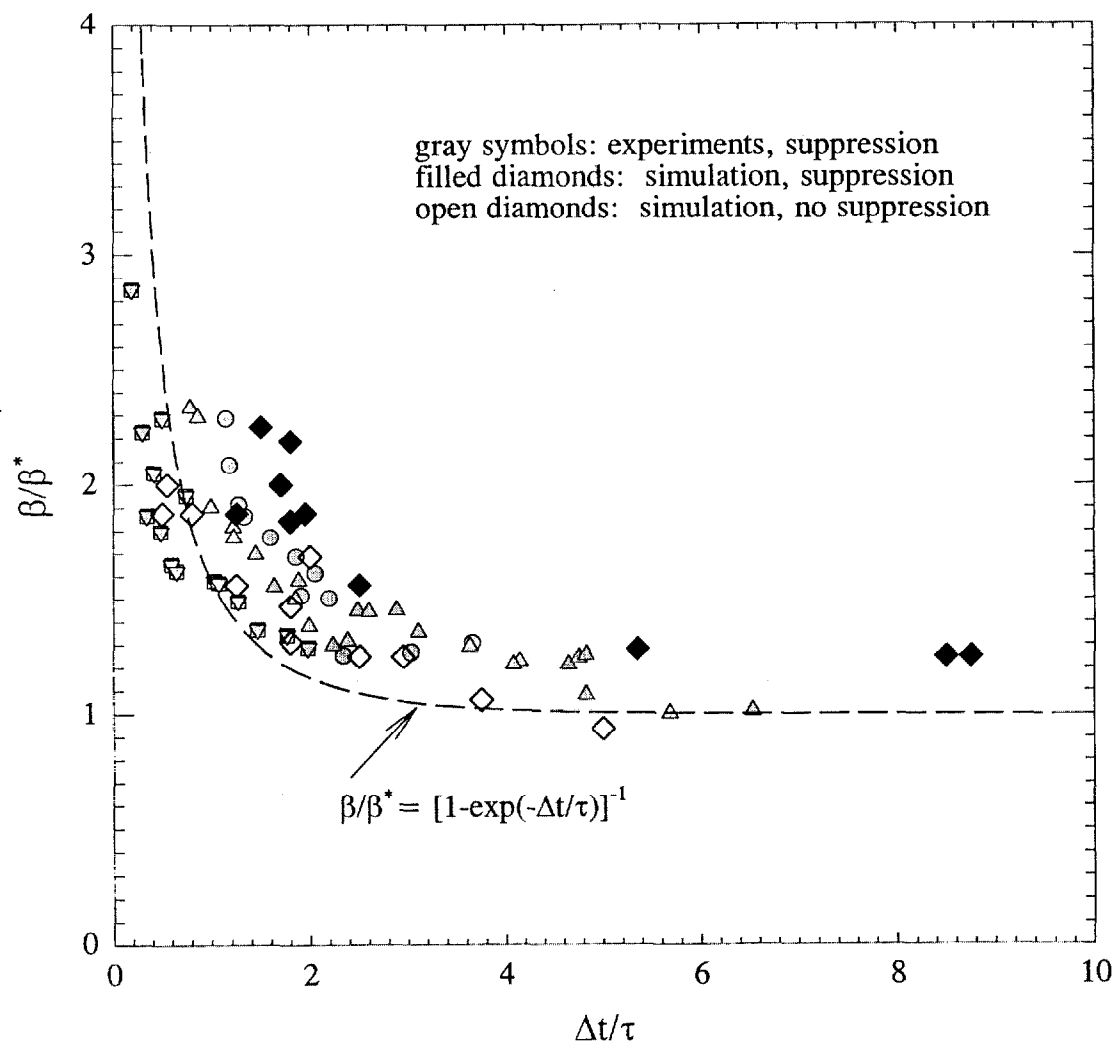


Figure 4. Suppression mass fraction of agent ( $N_2$  or  $CF_3Br$ ) normalized by cup burner values ( $\beta^*$ ) as a function of injection time interval normalized by characteristic residence time ( $\tau$ ). Gray symbols are experimental results keyed to Fig. 4; black diamonds are direct numerical simulations with  $N_2$ .

Figure 5. The disruption of a stabilized flame by the injection of nitrogen upstream of step. The darkness of the flame indicates the heat release rate per unit volume. The frames are separated by 0.01 s.

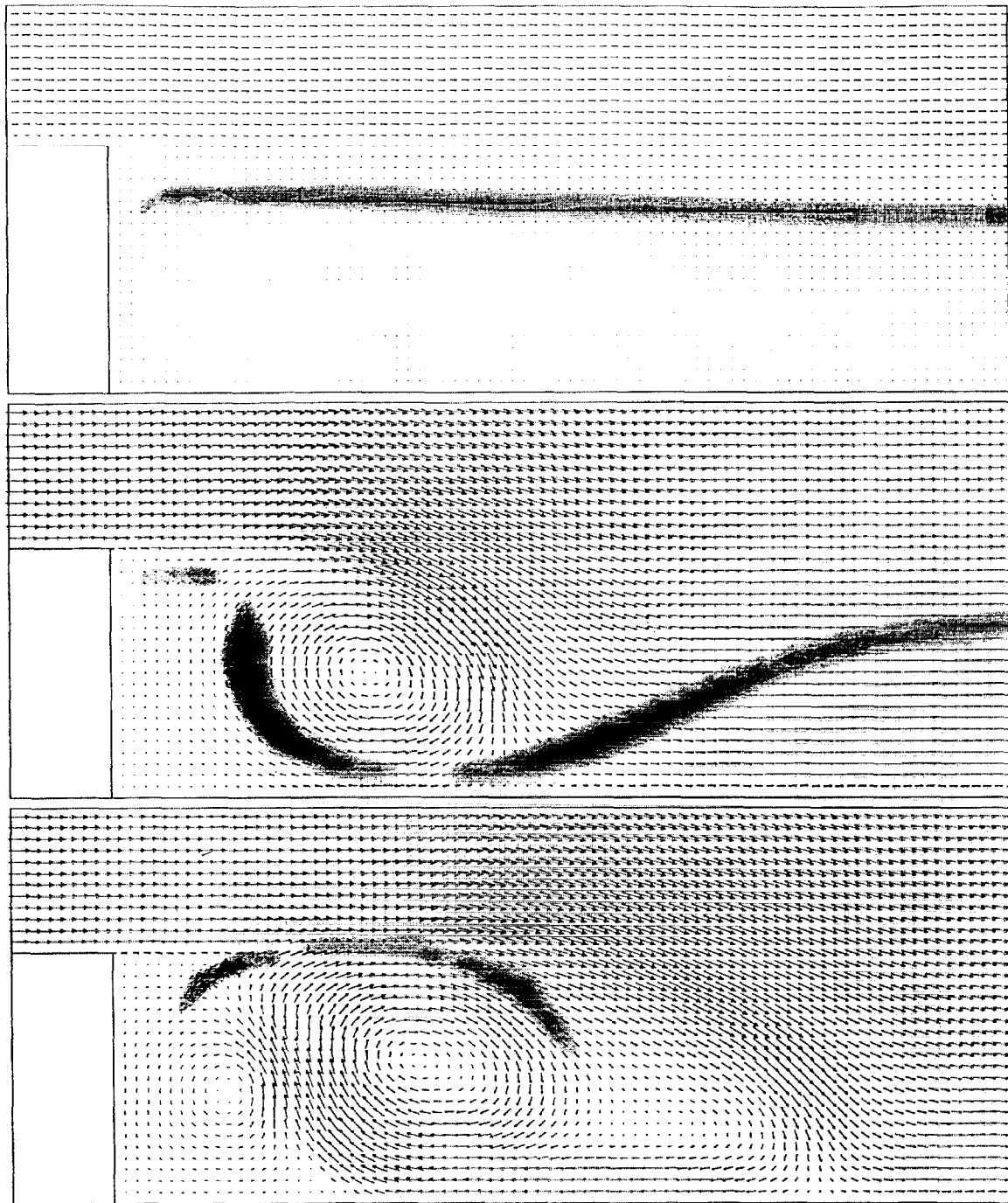


Figure 5. The disruption of a stabilized flame by the injection of nitrogen upstream of step. The darkness of the flame indicates the heat release rate per unit volume. The frames are separated by 0.02 s.